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The Cepheid Period-Luminosity Relation (The Leavitt Law) at Mid-Infrared Wavelengths: III. Cepheids in NGC 6822

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ABSTRACT

We present the first application of mid-infrared Period-Luminosity relations to the determination of a Cepheid distance beyond the Magellanic Clouds. Using archival IRAC imaging data on NGC 6822 from Spitzer we were able to measure single-epoch magnitudes for sixteen long-period (10 to 100-day) Cepheids at 3.6μm, fourteen at 4.5μm, ten at 5.8μm and four at 8.0μm. The measured slopes and the observed scatter both conform to the relations previously measured for the Large Magellanic Cloud Cepheids, and fitting to those relations gives apparent distance moduli of $\mu_{3.6} = 23.57 \pm 0.06$, $\mu_{4.5} = 23.55 \pm 0.07$, $\mu_{5.8} = 23.60 \pm 0.09$ and $\mu_{8.0} = 23.51 \pm 0.08$ mag. A multi-wavelength fit to the new IRAC moduli, and previously published BVRIJHK moduli, allows for a final correction for interstellar reddening and gives a true distance modulus of 23.49 ± 0.03 mag with E(B-V) = 0.26 mag, corresponding to a metric distance of 500 ± 8 kpc.

Subject headings: Stars: Variables: Cepheids, Galaxies: Individual (NGC 6822), Infrared: Stars, Galaxies: Distances and Redshifts

1. Introduction

We have embarked upon a program to recalibrate extragalactic distance scale using Cepheid variables observed at mid-infafred wavelengths. Two calibration papers (Freedman et al. 2008 and Madore et al. 2009) gave the first-epoch and then the dual-epoch calibrations

of the four mid-infared period-luminosity relations at 3.6, 4.5, 5.8 and 8.0μm based upon 76 Cepheids in the Large Magellanic Cloud as originally measured by the SAGE project (Meixner et al. 2006). Single-phase observations at these wavelengths have scatter contributed in almost equal measure by the natural width of the Cepheid instability strip and by the randomly sampled amplitudes of the individual Cepheids themselves. In the calibration papers we found that single-phase scatter of $\pm$0.14 mag is indicative of all four of the mid-infrared PL relations. In addition to the small scatter, the main advantage of observing Cepheids at these long wavelengths is the overall insensitivity of these magnitudes to interstellar extinction. For instance, compared to the optical B band, the extinction suffered by stars measured at 4.5μm (say) is reduced by a factor of 60 according to the extinction curve of Rieke & Lebovsky (1996, their Table 3). Thus any star with a line-of-sight B-band extinction 0.60 mag or less will have mid-IR extinction corrections of less than 1%. For the majority of extragalactic Cepheids reddenings are not all that high and this effectively means that mid-IR distance moduli are effectively true distance moduli.

Hubble (1925) was the first discover Cepheids in NGC 6822. In Hubble's own words NGC 6822 is "the first object definitely assigned to a region outside the galactic system" based on "familiar relations such as those connecting periods and luminosities of Cepheids ...". Hubble listed 11 Cepheids with periods ranging from 12 to 64 days. Nearly half a century later, Kayser's (1967) comprehensive examination of the resolved stars in NGC 6822 brought the number of Cepheids up to 13 and modernized the study of this galaxy by introducing both B and V observations of the main body of the galaxy. Kayser also selectively used UBV data of bright field stars along the line of sight to NGC 6822 to show that there was appreciable reddening (mostly foreground) between us and the Cepheids in NGC 6822. Kayser derived a reddening of E(B-V) = 0.27 mag; subsequent determinations ranged from 0.19 to 0.42 mag (see Gallart et al. 1996). Such a large range of reddening values suggests that a true distance modulus based, say, on V-band data, explicitly corrected for reddening, would immediately carry a systematic uncertainty whose range would amount to 0.7 mag. Indeed, most of the variance in subsequently published distances to NGC 6822 are strongly correlated with the adopted and/or derived reddenings.

More recent applications of the Cepheids in determining the distance to NGC 6822, following Kayser's (1967) study, include the multi-wavelength BVRI CCD study of six Cepheids by Gallart et al. (1996), and the near-infrared (H-band) study of 9 Cepheids by McAlary et al. (1983). More recently Gieren et al. (2006) obtained J and K photometry for 56 Cepheids in NGC 6822 based on a massive monitoring program undertaken by Pietrzynski et al. (2004) which resulted in the cataloging of 116 variables with periods ranging from 17 to 124 days.

2. NGC 6822: A Factor of 10 Beyond the LMC

The SAGE observations upon which the calibration of the mid-IR PL relations were derived from 43 seconds of integration time (for each of two epochs), resulted in typical errors of only ±0.05 mag for stars with periods around 30 days. This would suggest that for Cepheids a factor of ten times further away one could measure a similar sample of long-period Cepheids to the same signal-to-noise ratio in 43×10^2 sec, or approximately one hour.

The very nearby, Local Group, dwarf galaxy NGC 6822, is estimated to be at a distance of 500 kpc (that is, 10 times further away than the LMC). There are archival sets of mid-infrared (IRAC) observations of this galaxy consisting of 7 kilosecond mosaics. While the typical integration time per pixel amounts to only 240 sec, this is still a factor of about 6× longer than the LMC data used for our calibration. These images were taken by the SINGS team for other purposes, but they are publicly available from NED[1] and other NASA archives. The data we used were from the SINGS fifth (and final) data delivery. As described in the Fifth Data Delivery document[2], the SINGS mosaics were created from basic calibrated data (BCD) images made by Version 14 of the SSC IRAC pipeline. The mosaics were drizzled to a scale of 0.75 arcsec/pixel, and use the same surface brightness units as the original BCDs.

The IRAC images of NGC 6822 are all highly resolved into individual stars and our first task was to identify and recover the known Cepheids in this galaxy. Fortunately Pietrzynski et al. (2004) provide high-precision coordinates for all of the Cepheids discovered by them and these naturally included the objects previously identified by Hubble (1924) and Kayser (1967). The IRAC images have good astrometric solutions included with them so it was a simple matter to make preliminary identifications based solely on positional coincidences.

At fixed resolution (2 arcsec FWHM at the shortest IRAC wavelengths) moving a factor of ten further away (as compared to the LMC) does raise the question as to the effects of crowding and confusion on the photometry of NGC 6822 stars in general, and our Cepheids in particular. It is expected that simply by going from the optical to the mid-infrared some obvious nearby sources of crowding (blue stars) will disappear as others (intrinsically very red stars) rise up to take their place. OB stars that are part of the population coeval and co-located with the Cepheids are so blue that their effect on the Cepheid photometry should quickly become negligible in the IRAC data. Red supergiants, which would become even more luminous in comparison to the Cepheids as we move from the optical to the mid-IR, are sufficiently rare that they should not, a priori, pose much more of a problem to these

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[1] http://nedwww.ipac.caltech.edu/cgi-bin/nph-imgdata?objname=n6822

[2] http://data.spitzer.caltech.edu/popular/sings/20070410_enhanced_v1/Documents/sings_fifth_delivery_v2.pdf

datasets in the mid-IR than they do in the optical. The main source of confusion/crowding must then come from asymptotic giant branch (AGB) and extended-AGB stars. These objects are moderately luminous, very red and expected to be widely distributed over the entire face of any galaxy having an intermediate-aged population of stars. Extended AGB stars are so red that optical images are of limited use in predicting their possible influence on a case by case basis. In this regard we are entering uncertain territory.

The crowding of our sample can however be evaluated empirically. Visual inspection of each of the Cepheids and their immediate surroundings led to the following conclusions: nine out of the twenty-one longest-period ($P > 10$ days) Cepheids (NGC 6822:[K67] V02, V05, V06, V09, V12, V14, V19, V20 and V21) in our images of NGC 6822 were free and clear of any obvious contamination. Eight additional objects (V01, V03, V07, V08, V10, V15, V16 and V18) have faint nearby companions, and their photometry (especially V18 which has been dropped from the sample) may be compromised. Four Cepheids (V04, V11, V13 and V17) were totally crowded out at this resolution, and the observations of V19 appears to have been affected by a bad pixel. Depending, of course, on the color of the offending companion(s) the degree of contamination will also be a function of wavelength, with the reddest stars contaminating the longest-wavelength bands the most; V07 is an example of this, where its 8.0μm data are clearly contaminated well beyond what is seen at shorter wavelengths. All observations that were obviously compromised by visible companions have been dropped from further consideration.

For these short exposures, signal-to-noise considerations also reduced the final sample of data points available to us. The shorter-period (fainter) Cepheids progressively failed to be detected as we moved from the shortest to longest wavelengths. Most of the Cepheids were either undetected or confused in the 8.0μm band, whose limiting flux is about a factor of ten brighter than the 3.6μm limit. Only V01, V02, V03 and V06 came through relatively unscathed at this longest wavelength, and even then it is not clear that the longer-period star is not contaminated at 8.0μm. Since we use only Cepheids with periods less than 60 days or so V01 does not impact our solutions, but then again it leaves us with only one detection in this band; and so we focus all further discussion exclusively on the three shorter bandpasses.

The final sample of Cepheids and their total magnitudes are given in Table 1. SF fitting photometry was done using DAOPHOT (Stetson 1987). Aperture corrections, derived from Table 5.7 of the IRAC Data Handbook, were applied. The correction factors are considerable: for a 2 arcsec fitting radius they are 1.213, 1.234, 1.379 and 1.584 at 3.6, 4.5, 6.8 and 8.0μm, respectively. Finally, flux densities were converted to the IRAC magnitude system using the zero-points of Reach et al. (2005) which correspond exactly to the SAGE zero points used for the LMC calibration.

3. IRAC Mid-Infrared Period-Luminosity Relations

Sixteen Cepheids in NGC 6822 have good 3.6μm photometry. The numbers monotonically decline to 14, 10 and 4 Cepheids at 4.5, 6.8 and 8.0μm, respectively. The Period-Luminosity relations based on the data in Table 1 are shown in Figure 1. The dashed lines are least-squares fits to the zero-point calibrating relations based on LMC Cepheids as given in Madore et al. (2009). The flanking solid lines are set at $\pm$0.20 mag and appear to encompass the majority of data points. Modulo the slightly increased scatter of the NGC 6822 data as compared to the LMC ($\pm$0.14 mag) data, the calibrating relations appear to be a good fit to the data. There is no evidence here for any significant difference between the LMC PL slope and that appropriate to the NGC 6822 data.

The apparent moduli derived from fitting the LMC relations to the NGC 6822 data are given at the bottom of Table 3. These three independently determined moduli agree to within $\pm$0.05 mag of each other. And, given their very low sensitivity to extinction, they should already be a very close approximation to the true modulus for NGC 6822.

4. Multi-Wavelength Solutions

Table 2 also contains a selection of additional apparent distance moduli based on slightly different (usually larger) Cepheid samples measured at optical through near-infrarded wavelengths. These moduli are derived from the originally published Cepheid data, consistently differenced against the Key Project (VI: Freedman et al. 2001, BR: Madore & Freedman 1991) and Persson et al. (2004) Period-Luminosity relations at BVRI and JHK, respectively.

The moduli in Table 2 are plotted as a function of inverse wavelength in Figure 2. Larger apparent distance (upward in the plot) as a function of bluer wavelengths (to the right) are interpreted here as being exclusively due to (wavelength-dependent) line-of-sight extinction. A weighted fit to a standard Galactic entinction curve (Cardelli et al. 1989) is shown as a solid line, flanked by one-sigma error lines. The slope of the fit corresponds to a color excess of E(B-V) = 0.26 mag, while the y intercept gives a true modulus of 23.49$\pm$0.03 mag. This corresponds to a metric distance of 500$\pm$6 kpc.

There is a slight discrepancy however. The two data points at J and K (plotted as open circles) are shown but not included in the solution. Based on near-infrared observations of over 50 Cepheids in NGC 6822 (Gieren et al. 2006) these two data points have exceedingly high statistical weight. But they are both systematically at variance with the IRAC data. We do not currently have an explanation for the difference. Gieren et al. mention applying corrections to their data to get them onto the Persson et al. (2004) system, but those

corrections, as quoted, are small. The only other near-infrared data point that might be used to adjudicate is the H-band measurement of McAlary et al. (1983). This is early-epoch aperture photometry data and of relatively low weight, but in fact it agrees to within one sigma with both solutions. And so it is of little help here. The best that we can do at this point is to note the problem and quantify it by stating that ignoring the IRAC data and in deference to the JK photometry leads to a much higher value of the reddening (E(B-V) = 0.30 mag) and consequently a lower value for the true distance modulus, μ_o = 23.32±0.04 mag.

5. Conclusions

We have demonstrated that Cepheids can be detected and easily measured by Spitzer at mid-infrared wavelengths out to at least a distance of 500 kpc with almost trivial (4 min) exposure times. Crowding (from AGB stars primarily) is starting to become noticeable at this distance, but sufficient numbers of Cepheids are free from crowding that it was possible to extract uncontaminated magnitudes for over a dozen Cepheids at 3.5μm and a monotonically decreasing number at longer wavelengths, due to the additive affects of waning sensitivity, slowly decreasing spatial resolution, and clearly increasing crowding and confusion.

The four independent mid-infrared IRAC distance moduli agree to within five percent and when combined with optical (BVRI) data they give a true distance modulus of 23.49±0.03 mag (500 kpc) and a reddening of E(B-V) = 0.26 mag. A discepancy (at the 0.15 mag level) with previously published near-infrared (JK) data is noted, but no explanation of the systematic offset is obvious.

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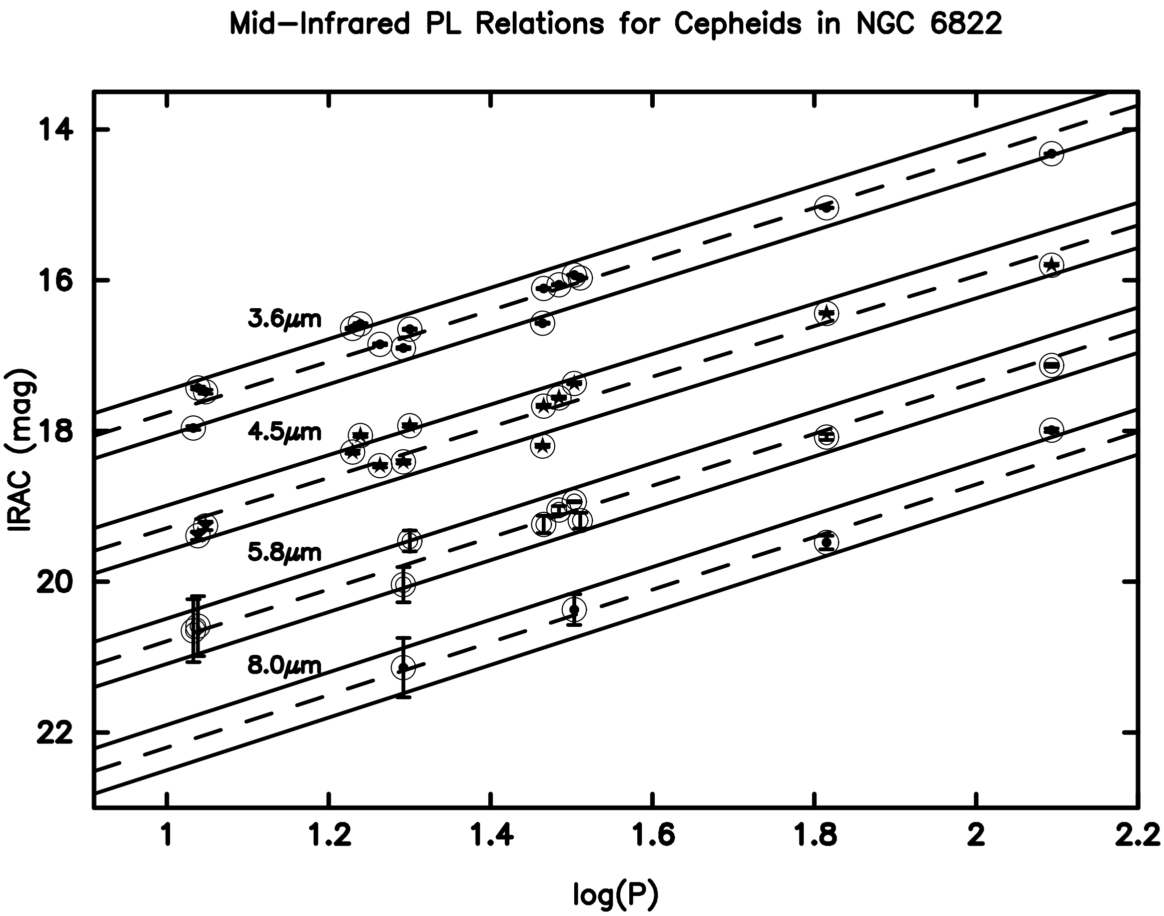

Fig. 1 – Mid-Infrared Period-Luminosity realtions for Cepheids in NGC 6822. Dashed lines are fits to the fiducial relations of Madore et al. (2009) based on LMC data and an adopted true distance to the LMC of 18.50 mag. The flanking solid lines are offset from the fit by ±0.20 mag and appear to represent the full width of each of the relations.

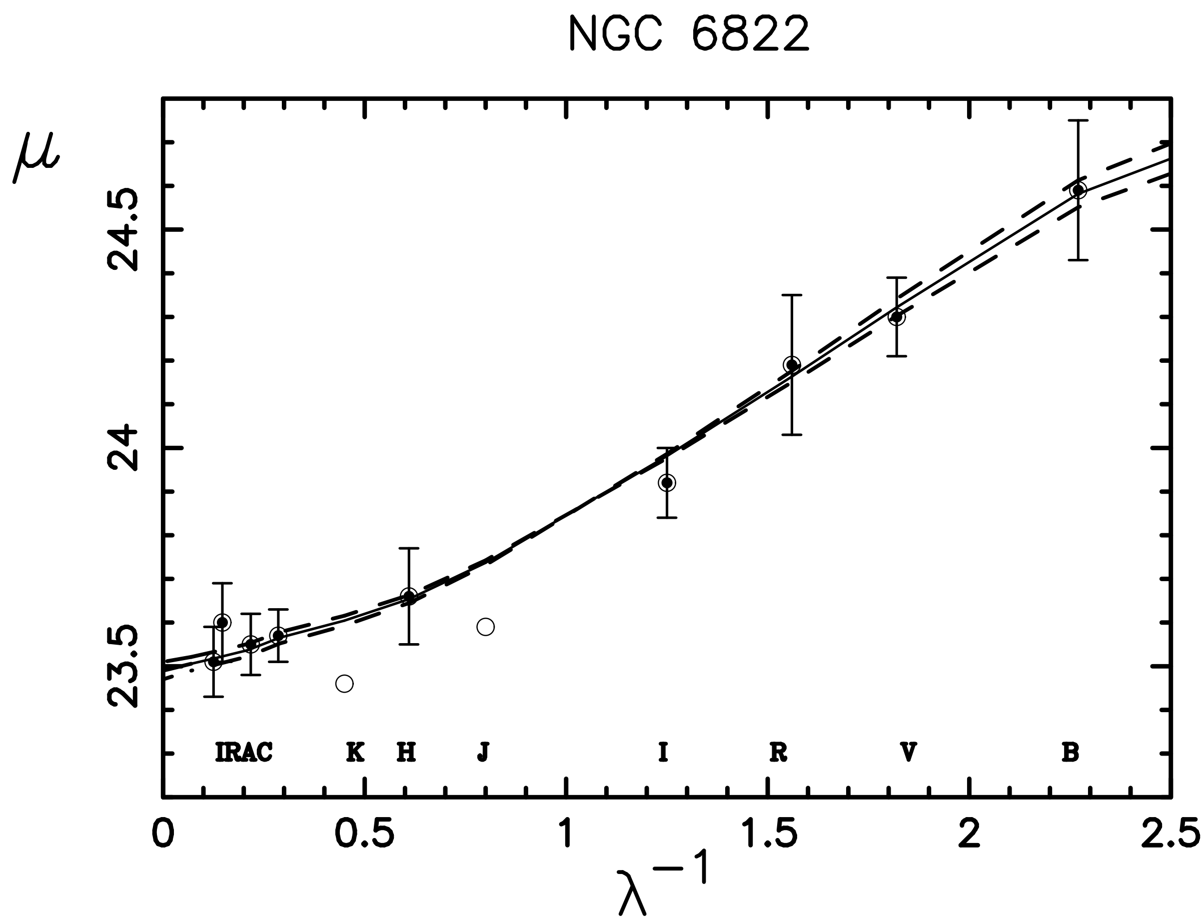

Fig. 2 – A multi-wavelength fit of a standard Galactic extinction curve to the apparent distance moduli to NGC 6822 derived from Cepheids. The two open circles represent J and K moduli that are clearly at variance with the rest of the data; they are plotted but not included in the over-all fit. The fit gives a reddening of E(B-V) = 0.26 mag and a true distance modulus of $\mu_o = 23.49 \pm 0.03$ mag.

Table 1. Mid-Infrared (IRAC) Magnitudes for Cepheids in NGC 6822

Cepheid	log(P) (days)	3.6μm (mag)	4.5 mum (mag)	5.8μm (m ag)	8.0μm (mag)
NGC 6822:[K67] V01	2.093	14.32	14.30	14.13	13.49
		0.003	0.006	0.019	0.024
NGC 6822:[K67] V02	1.815	15.04	14.94	15.08	14.98
		0.004	0.005	0.040	0.090
NGC 6822:[K67] V03	1.574	15.44	15.51	15.17	15.83
		0.006	0.009	0.044	0.182
NGC 6822:[K67] V05	1.510	15.97	. . .	16.19	. . .
		0.006	. . .	0.105	. . .
NGC 6822:[K67] V06	1.503	15.93	15.87	15.94	15.87
		0.006	0.010	0.008	0.204
NGC 6822:[K67] V07	1.484	16.06	16.06	. . .	. . .
		0.009	0.014	. . .	. . .
NGC 6822:[K67] V08	1.466	16.11	16.17	16.24	. . .
		0.009	0.015	0.116	. . .
NGC 6822:[K67] V09	1.464	16.57	16.70	. . .	. . .
		0.010	0.015	. . .	. . .
NGC 6822:[K67] V10	1.300	16.65	16.43	16.46	. . .
		0.011	0.019	0.138	. . .
NGC 6822:[K67] V12	1.292	16.90	16.91	17.04	. . .
		0.013	0.023	0.234	. . .
NGC 6822:[K67] V14	1.263	16.85	16.96	. . .	. . .
		0.013	0.025	. . .	. . .
NGC 6822:[K67] V15	1.239	16.58	16.56	. . .	. . .
		0.012	0.020	. . .	. . .
NGC 6822:[K67] V16	1.229	16.64	16.78	. . .	. . .
		0.011	0.021	. . .	. . .
NGC 6822:[K67] V19	1.048	17.48	17.76	. . .	. . .
		0.026	0.056	. . .	. . .
NGC 6822:[K67] V20	1.038	17.43	17.89	17.59	. . .
		0.019	0.054	0.398	. . .
NGC 6822:[K67] V21	1.033	17.96	. . .	17.65	. . .
		0.026	. . .	0.418	. . .

Table 2. Apparent (Cepheid) Moduli for NGC 6822

Bandpass	Apparent Modulus	Reference
B	24.59 (0.16)	Gallart et al. (1996)
V	24.30 (0.09)	Pietrzynski et al. (2004)
R	24.19 (0.16)	Gallart et al. (1996)
I	23.92 (0.08)	Pietrzynski et al. (2004)
J	23.59 (0.02)	Gieren et al. (2006)
H	23.66 (0.11)	McAlary et al. (1983)
K	23.46 (0.02)	Gieren et al. (2006)
3.4μm	25.57 (0.05)	this paper
4.5μm	25.55 (0.07)	this paper
5.8μm	25.60 (0.09)	this paper
8.0μm	25.51 (0.08)	this paper